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Amit Rawal and Rajesh Anandjiwala
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# Relationship between Process Parameters and Properties of Multifunctional Needlepunched Geotextiles

**AMIT RAWAL**[1,*] **AND RAJESH ANANDJIWALA**[1,2]
[1]*CSIR, National Fibre, Textile and Clothing Centre*
*Port Elizabeth 6000, South Africa*
[2]*Department of Textile Science, Faculty of Science*
*Nelson Mandela Metropolitan University*
*Port Elizabeth, South Africa*

**ABSTRACT:** Geotextiles are commonly produced by needlepunching technology and generally used for various civil engineering applications. Some of these applications require geotextiles to perform more than one function including separation, drainage, and filtration. In this study, the effect of process parameters, namely, feed rate, stroke frequency, and depth of needle penetration has been investigated on various properties of needlepunched geotextiles. These process parameters are then empirically related with the properties of geotextiles. Subsequently, an expert system has been developed to predict the properties of geotextiles for any desired application.

**KEY WORDS:** geotextiles, fiber orientation, pore size, transmissivity, permeability, needlepunched nonwoven, multifunctional, expert system.

## INTRODUCTION

NONWOVEN GEOTEXTILES ARE complex three-dimensional structures formed by random arrangement of fibers. They are permeable and compressive textile materials and belong to the geosynthetic group which also includes geogrids, geonets, geomembranes, and geocomposites. The

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*Author to whom correspondence should be addressed. Department of Metallurgy and Materials Engineering (MTM), Katholieke Universiteit Leuven, Kasteelpark Arenberg, 44 B-3001 Leuven (Heverlee), Belgium. E-mail: amitrawal77@hotmail.com and amitrawal77@yahoo.com
Figures 1–9 appear in color online: http://jit.sagepub.com

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production processes of nonwoven geotextiles involve fiber production, fiber preparation, web formation, web bonding, and finishing. Thus, continuous filaments or short staple fibers are initially arranged in the form of a fibrous web in various orientations (random, cross, parallel, or composite). Subsequently, these fibrous webs are bonded together by means of chemical, thermal, or mechanical bonding processes. Mechanical bonding is generally carried out by a needlepunching process for producing geotextile structures. The needlepunched fabrics are produced by the penetrating action of barbed needles which re-orientates and intermingles the fibers from a horizontal to a vertical direction. This forms a three-dimensional intermingled structure which fulfils the necessary requirements of geotextiles.

Needlepunched nonwoven geotextiles are extensively used in civil engineering applications including road and railway construction, landfills, land reclamation, sea defence, and slope stabilization. Such applications require geotextiles to perform more than one function including filtration, drainage, and separation. The function of geotextile filtration is to retain the soil while allowing the passage of the liquid [1]. The drainage function of geotextiles is to transmit the liquid in the plane of the fabric without the loss of soil particles. Therefore, the filtration and drainage functions differ mainly in terms of direction of liquid flow. The separation function of geotextiles involves segregation followed by retention of soil particles. Thus, the geotextile structure should be designed to fulfill the criteria demanded by the end-use applications. For instance, the geotextile products used in rail track construction must possess high strength, excellent filtration behavior, and drainage capacity. Furthermore, the performance characteristics of geotextiles are dependent upon the fiber and structural mechanics of the fabric developed during the manufacturing process. There are several material and process parameters (fiber, web, needle, needlepunching, and finishing) that can affect the performance characteristics of geotextiles. In addition, the structural coherence in needlepunched fabric depends upon the frictional characteristics and interaction of constituent fibers [2–4].

Therefore, the overall aim of the work reported in the present article is to design the geotextile structures by optimizing the process parameters to achieve desired fabric properties. The geotextiles produced exhibit multifunctional properties and high performance characteristics for various applications including waste and water containment, landfill, and other water-retaining structures.

## EXPERIMENTAL

A central composite design was employed with three design factors at five levels, namely, feed rate (FR) to carding machine, stroke frequency (SF),

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*Table 1. Experimental design for production of geotextiles.*

| Sample ID | FR (m/min) | SF ($\text{min}^{-1}$) | NP (mm) |
|---|---|---|---|
| 1 | −1 | −1 | −1 |
| 2 | 1 | −1 | −1 |
| 3 | −1 | 1 | −1 |
| 4 | 1 | 1 | −1 |
| 5 | −1 | −1 | 1 |
| 6 | 1 | −1 | 1 |
| 7 | −1 | 1 | 1 |
| 8 | 1 | 1 | 1 |
| 9 | 1.682 | 0 | 0 |
| 10 | −1.682 | 0 | 0 |
| 11 | 0 | 1.682 | 0 |
| 12 | 0 | −1.682 | 0 |
| 13 | 0 | 0 | 1.682 |
| 14 | 0 | 0 | −1.682 |
| 15 | 0 | 0 | 0 |

*Table 2. Coded and actual values of the process parameters.*

| Variables | $-\alpha$ | −1 | 0 | 1 | $\alpha$ |
|---|---|---|---|---|---|
| FR (m/min) | 0.4 | 0.48 | 0.6 | 0.72 | 0.8 |
| SF ($\text{min}^{-1}$) | 300 | 381 | 500 | 619 | 700 |
| NP (mm) | 7 | 8 | 9.5 | 11 | 12 |

and depth of needle penetration (NP), as shown in Table 1. In order to simplify the recording and processing of the experimental data, the factor levels were selected such that the upper level corresponds to +1, the lower level to −1, and the middle level to zero. The coded levels and the actual values of these factors are defined in Table 2. Later, a series of needlepunched geotextile structures from hollow polyester staple fiber (6 dtex, 60 mm) have been produced with laboratory equipment available to the authors based upon experimental design defined in Table 1. The hollow fiber provides the required drainage and filtration properties in addition to fulfilling the separation requirements. The needlepunched geotextile structures were produced initially by opening the staple fiber bale and then orientating the fibers to cross-direction using a cross-lapper to form a web of required area density. Following the production of needlepunched geotextiles, standard tests were performed on the geotextiles to determine their pore size distribution [5], transmissivity [6], and permeability [7]. Furthermore, the fiber orientation angle with respect to cross-machine direction was digitally measured and analyzed on commercially available

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image analysis software, analySIS version 3.2. The histograms and fitted curves of the relative frequency of fibers for 10° orientation angle interval with respect to the cross-machine direction (90° indicating the machine direction) were computed to characterize the orientation distribution function (ODF).

## RESULTS AND DISCUSSION

### Influence of Process Parameters on Geometrical Properties of Needlepunched Geotextiles

The effect of process parameters was investigated on the geometrical properties including fiber orientation and pore size distributions of geotextile structures. The Fourier series was fitted to the measured relative frequency of the fibers and a good correlation between the measured and predicted relative frequencies was obtained (shown in Table 3). Therefore, these mathematical models were used for predicting the fiber orientation by

*Table 3. Mathematical models for orientation distribution function of needlepunched geotextiles.*

| Sample ID | Orientation distribution function (ODF) | $R^2$ |
|---|---|---|
| 11 (SF = 700 min$^{-1}$) | $5.56 + 0.27\cos\theta - 1.12\cos 2\theta - 1.28\cos 3\theta - 2.74\cos 4\theta + 0.29\cos 5\theta - 0.21\cos 6\theta + 0.31\cos 7\theta - 0.57\cos 8\theta - 0.24\cos 9\theta + 0.38\cos 10\theta - 0.27\cos 11\theta + 0.3\cos 12\theta - 0.33\cos 13\theta + 0.29\cos 14\theta$ | 0.90 |
| 12 (SF = 300 min$^{-1}$) | $5.56 - 0.29\cos\theta - 0.81\cos 2\theta - 1.25\cos 3\theta - 2.45\cos 4\theta + 0.46\cos 5\theta - 1.22\cos 6\theta + 0.20\cos 7\theta - 0.25\cos 8\theta - 0.12\cos 9\theta - 0.125\cos 10\theta - 0.029\cos 11\theta + 0.51\cos 12\theta - 0.005\cos 13\theta - 0.23\cos 14\theta$ | 0.90 |
| 13 (NP = 12 mm) | $5.56 - 0.82\cos\theta - 0.52\cos 2\theta - 0.5\cos 3\theta - 2.04\cos 4\theta - 0.279\cos 5\theta - 0.91\cos 6\theta - 0.24\cos 7\theta - 0.11\cos 8\theta + 0.22\cos 9\theta - 0.81\cos 10\theta - 0.46\cos 11\theta - 0.31\cos 12\theta - 0.62\cos 13\theta + 0.29\cos 14\theta$ | 0.90 |
| 14 (NP = 7 mm) | $5.56 - 0.66\cos\theta + 0.211\cos 2\theta - 0.88\cos 3\theta - 1.99\cos 4\theta - 0.35\cos 5\theta - 0.72\cos 6\theta - 0.53\cos 7\theta - 0.62\cos 8\theta - 0.092\cos 9\theta + 0.22\cos 10\theta + 0.082\cos 11\theta - 0.11\cos 12\theta - 0.06\cos 13\theta + 0.48\cos 14\theta$ | 0.79 |
| 15 (NP = 9.5 mm) | $5.56 - 0.41\cos\theta - 0.09\cos 2\theta - 0.98\cos 3\theta - 2.02\cos 4\theta - 0.89\cos 5\theta - 0.82\cos 6\theta + 0.22\cos 7\theta - 1.05\cos 8\theta + 0.49\cos 9\theta - 0.32\cos 10\theta - 0.037\cos 11\theta + 0.5\cos 12\theta - 0.03\cos 13\theta + 0.41\cos 14\theta$ | 0.87 |

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individually varying the needlepunching parameters, i.e., depth of needle penetration and stroke frequency at a constant feed rate of 0.6 m/min. It was found that an increase in the depth of needle penetration causes an increase in the relative frequency of the fibers oriented in the machine direction as shown in Figure 1(a). This may be due to the fact that the fibers have to take a longer path, due to higher depth of needle penetration from surface to the thickness direction, and during the process, some of the fibers would be released. On recovery, the fibers preferentially oriented in the cross-machine

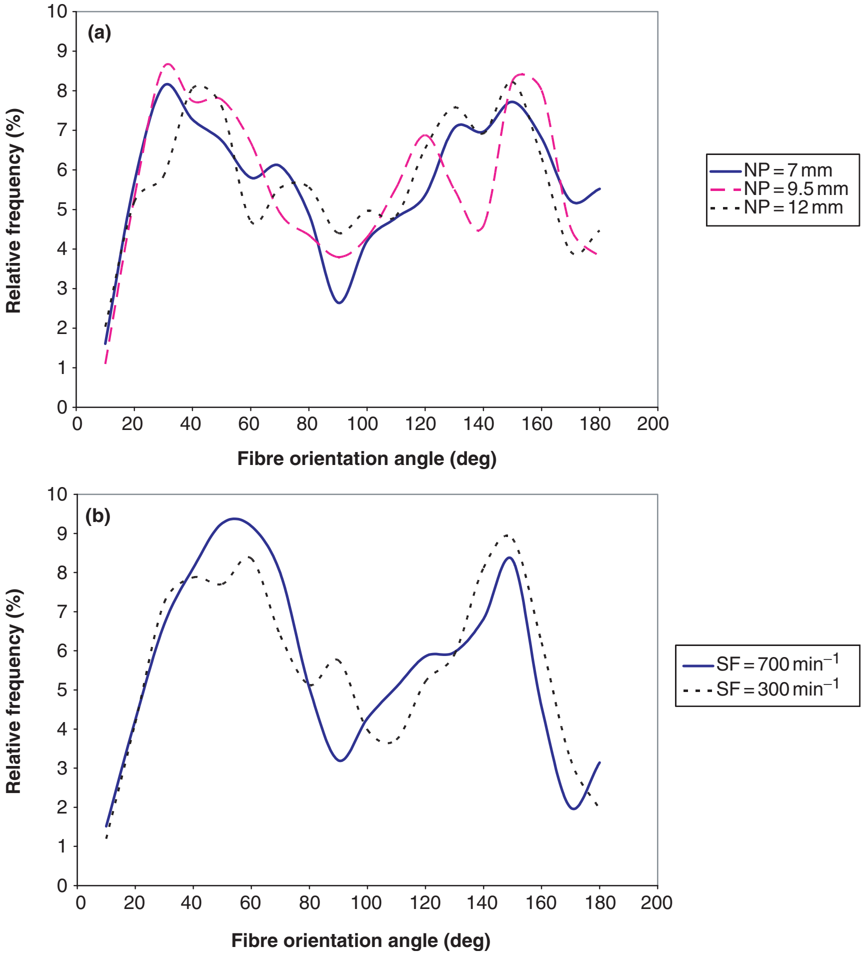

**FIGURE 1.** Effect of (a) depth of needle penetration and (b) stroke frequency on fiber orientation distribution.

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direction would tend to reorientate in the machine direction. However, an increase in stroke frequency reduces the relative frequency of the fibers in the machine direction, as shown in Figure 1(b). The trailing component of preferentially oriented fibers, lying on the surface of the fibrous web would come in contact with the needles repeatedly due to an increase in stroke frequency. However, the fibers recover back due to high elastic recovery and this may change the orientation of trailing component of fibres from machine to cross-machine direction.

Moreover, an increase in stroke frequency or depth of needle penetration reduces the pore size of geotextiles, as shown in Figures 2a and 2b. This is attributed to the fiber damage at higher needle penetration or stroke frequency causing disintegration into small constituents. This causes significant reduction especially in larger pore sizes, i.e., $O_{95}$ and $O_{98}$, which lowers the filtration efficiency of the geotextiles. The $O_{98}$ values are reduced from 357 μm to 306 μm at needle penetrations of 7 mm and 12 mm, respectively. Similarly, the $O_{98}$ values are reduced from 353 μm to 281 μm at

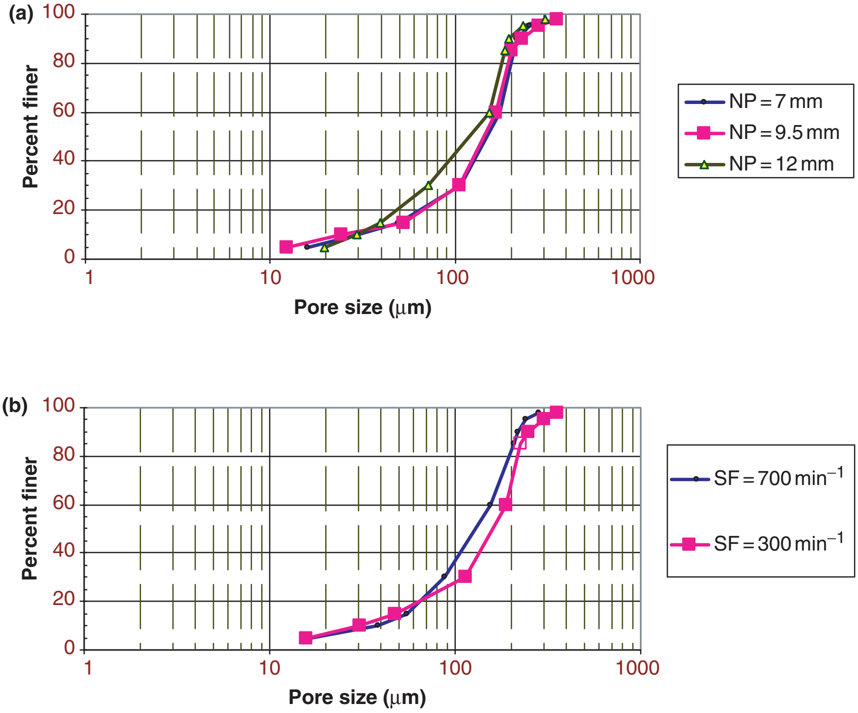

**FIGURE 2.** Effect of (a) depth of needle penetration and (b) stroke frequency on pore size distribution.

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stroke frequencies of 300 $\text{min}^{-1}$ and 700 $\text{min}^{-1}$, respectively. $O_{98}$ is defined as the particle diameter at which 98% by weight is retained on the geotextiles [8].

## Effect of Process Parameters on Hydraulic Properties of Needlepunched Geotextiles

The in-plane transmissivity and across the plane permeability characteristics of needlepunched geotextiles transfer the liquid in horizontal and vertical directions, respectively. Transmissivity of needlepunched geotextiles was measured under a normal stress of 100 kPa. Figure 3 shows the effect of stroke frequency and feed rate on the transmissivity behavior of needlepunched geotextile. An increase in stroke frequency reorients higher number of fibers from horizontal to vertical direction, which decreases the transmissivity of geotextiles. Furthermore, on increasing the feed rate, the number of fibers present in the horizontal direction will increase and it enhances the geotextiles' transmissivity as the fibers are hollow and the pores in the in-plane direction will increase correspondingly. The effect of higher needle penetration is similar to that of stroke frequency, as shown in Figure 4. Moreover, the effect of stroke frequency and depth of needle penetration was also investigated as shown in Figure 5. It was found that

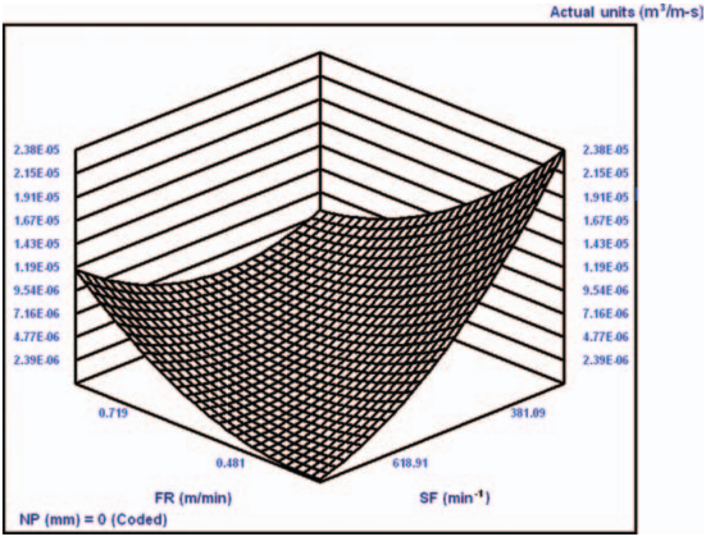

**FIGURE 3.** Effect of stroke frequency and feed rate on geotextile transmissivity at a depth of needle penetration of 9.5 mm.

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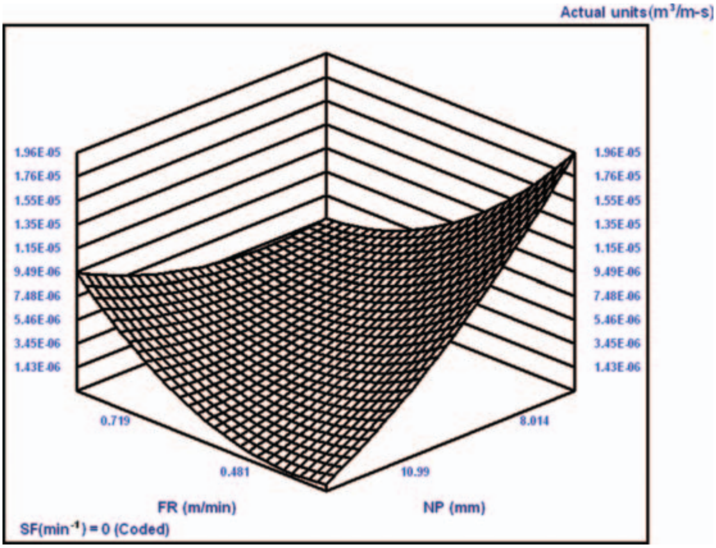

**FIGURE 4.** Effect of depth of needle penetration and feed rate on geotextile transmissivity at a stroke frequency of 500 min$^{-1}$.

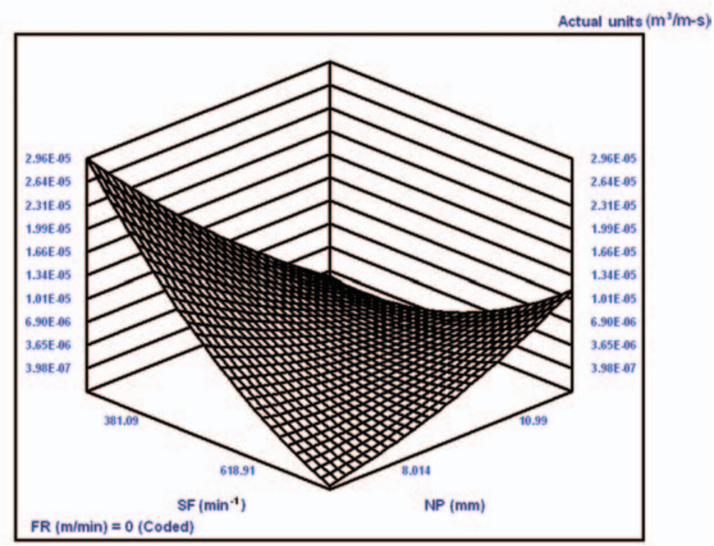

**FIGURE 5.** Effect of stroke frequency and depth of needle penetration on geotextile transmissivity at a feed rate of 0.6 m/min.

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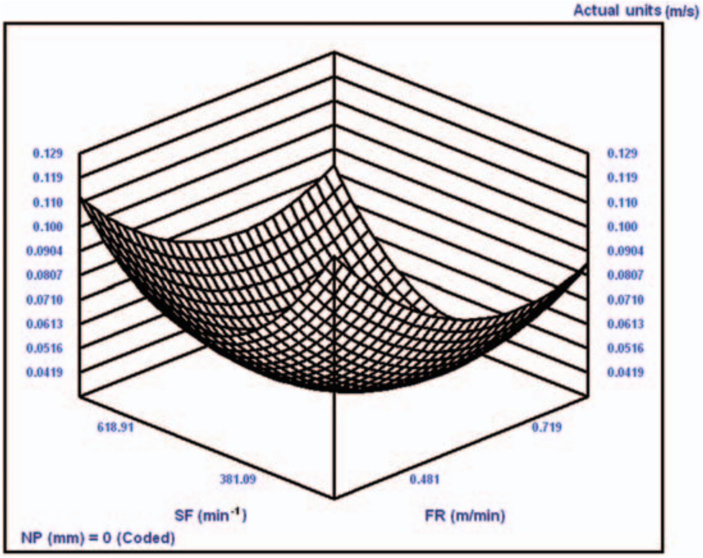

**FIGURE 6.** Effect of stroke frequency and feed rate on geotextile permeability at a depth of needle penetration of 9.5 mm.

transmissivity of the geotextiles is reduced when there is an increase in stroke frequency but reduction in needle penetration.

The effect of process parameters on permeability characteristics was contrary to that of transmissivity behavior. Figure 6 shows the effect of stroke frequency and feed rate on the permeability of needlepunched geotextile. It has been observed that lower feed rates and stroke frequencies increase the permeability characteristics of needlepunched nonwovens. This is because the lower feed rate results in fewer fibres in the structure and form relatively larger pores, especially at lower stroke frequencies. However, increases in both feed rate and stroke frequency have reduced the permeability of the needlepunched nonwovens as the pore size decreases with the increase in the number of fibres. A further increase in stroke frequency increases the number of hollow fibers in the vertical direction. This enhances the permeability of geotextiles even at a higher feed rate. A similar trend was found in the case of depth of needle penetration and feed rate on the permeability of geotextile [9] as shown in Figure 7. Furthermore, reduction in both stroke frequency and depth of needle penetration has revealed an increase in the permeability of geotextiles as shown in Figure 8.

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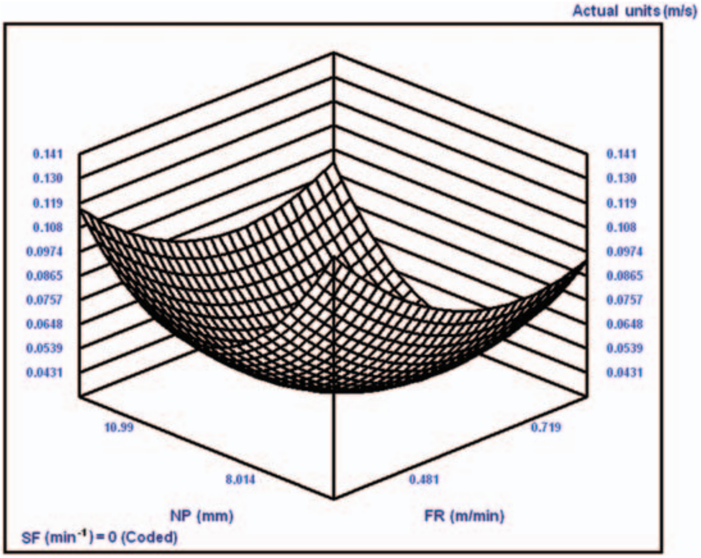

**FIGURE 7.** Effect of depth of needle penetration and feed rate on geotextile permeability at a stroke frequency of 500 min$^{-1}$.

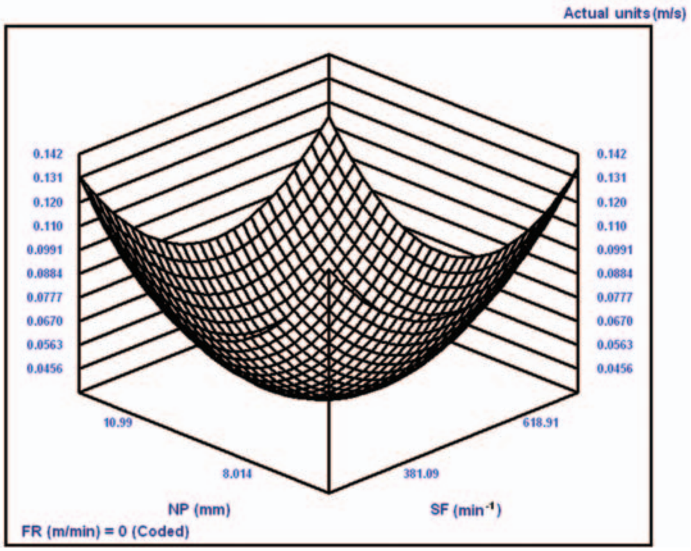

**FIGURE 8.** Effect of stroke frequency and depth of needle penetration on geotextile permeability at a feed rate of 0.6 m/min.

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This is attributed to the lower amount of needle penetration and stroke frequency which is sufficient to attain higher permeability characteristics in geotextiles. Increase in either or both needle penetration and/or stroke frequency reduces permeability, because permeability is mainly dependent upon the geometry of the porous structure [10]. The tortuosity, defined as the ratio of path length of the flow to the length of the porous material, determines the amount of fluid transmission, as given in the Kozeny equation below:

$$K = \frac{c\phi^3}{\tau\sum^2}$$

where $K$ is the permeability of the porous material, $\phi$ is the porosity, $\tau$ is the tortuosity, $\sum$ is the specific surface, and $c$ is a dimensionless constant.

Hence, an increase in stroke frequency or depth of needle penetration causes fiber damage resulting in smaller constituents, which increases the path length of the flow. A further increase in stroke frequency or depth of needle penetration increases the number of hollow fibers in the vertical direction.

## Development of Empirical Models for Needlepunched Geotextiles

Initially, the Fourier series was fitted to the measured relative frequency of the fibers as shown in the following equation:

$$y(\theta) = a_0 + b_k \cos k\theta$$

where $y(\theta)$ is the relative frequency at an orientation angle $\theta$, $n$ is number of intervals, $k$ is any positive integer, and $a_0$ and $b_k$ are defined as follows:

$$a_0 = \frac{\sum_{i=1}^{n} y_i}{n} \quad \text{and} \quad b_k = \frac{2}{n}\sum_{i=1}^{n} y_i \cos k\theta, \quad 0 \le \theta \le \pi$$

A good correlation between the measured and predicted relative frequencies was obtained, as shown in Table 3. Furthermore, the empirical relations between the main process parameters, namely, feed rate, stroke frequency, and depth of needle penetration and the fabric properties were formulated using the multiple regression technique. These models are based upon the coded values of the parameters, i.e., the minimum and the maximum values are $-1$ and 1, respectively. Finally, the linear relationships were formed with the actual data. Table 4 shows the equations of the empirical models along

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Table 4. *Empirical models for geotextile properties (coded values).*

| Geotextile property | Empirical models | Correlation coefficient | *F*-value | Significance (%) |
|---|---|---|---|---|
| Fabric area density | $306.91 + 49.41(FR) - 11.96(SF) - 10.2(NP)$<br>$- 2.06(FR)(SF) - 3.06(FR)(NP) + 0.905(SF)(NP)$<br>$+ 0.605(FR)^2 - 5.145(SF)^2 + 4.752(NP)^2$ | 0.96 | 7.14 | 97.83 |
| Fabric thickness | $3.257 + 0.421(FR) - 0.219(SF) - 0.314(NP)$<br>$- 0.0662(FR)(SF) - 0.0613(FR)(NP) + 0.0237(SF)(NP)$<br>$- 0.013(FR)^2 - 0.0148(SF)^2 - 0.0042(NP)^2$ | 0.99 | 29.69 | 99.92 |
| Tensile strength (machine direction) | $224.94 + 41.02(FR) + 31.99(SF) + 23.89(NP)$<br>$+ 10.37(FR)(SF) + 3.541(FR)(NP) - 0.964(SF)(NP)$<br>$- 4.44(FR)^2 - 19.55(SF)^2 - 14.11(NP)^2$ | 0.98 | 11.89 | 99.3 |
| Tensile strength (cross-direction) | $367.34 + 74.94(FR) + 37.61(SF) + 39.44(NP)$<br>$+ 16.08(FR)(SF) + 5.23(FR)(NP) - 3.095(SF)(NP)$<br>$- 9.044(FR)^2 - 34.08(SF)^2 - 28.02(NP)^2$ | 0.99 | 20.56 | 99.8 |
| Permeability | $34.95 - 8.362(FR) - 0.845(SF) - 1.456(NP)$<br>$+ 1.066(FR)(SF) + 1.491(FR)(NP) - 1.241(SF)(NP)$<br>$+ 6.389(FR)^2 + 11.5(SF)^2 + 13.6(NP)^2$ | 0.94 | 8.27 | 99.86 |
| Transmissivity (cross-direction) | $[0.436 - 0.375(FR) - 2.27(SF) - 1.87(NP)$<br>$+ 1.84(FR)(SF) + 1.57(FR)(NP) + 2.9\ (SF)(NP)$<br>$+ 1.88(FR)^2 + 2.1(SF)^2 + 1.51(NP)^2]\ X\ 1E - 06$ | 0.77 | 1.74 | 79.91 |

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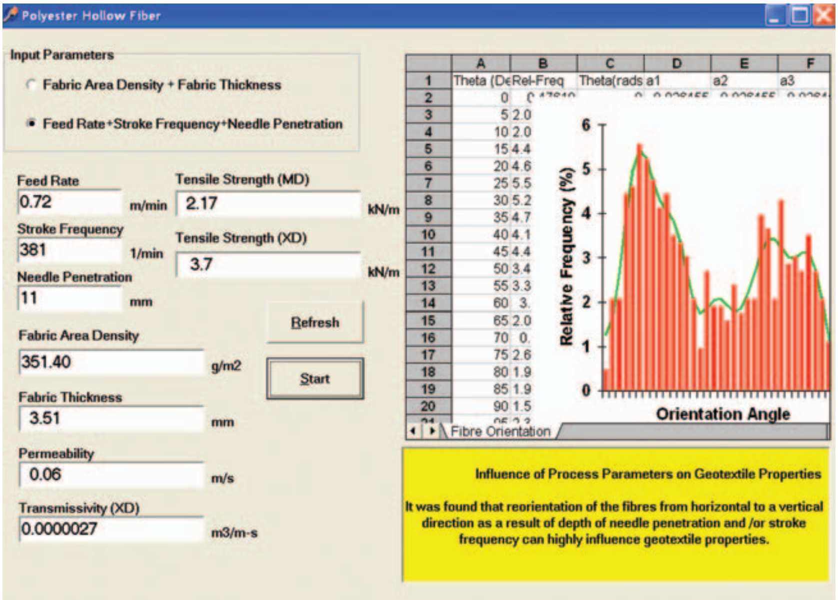

Input Parameters

○ Fabric Area Density + Fabric Thickness

● Feed Rate+Stroke Frequency+Needle Penetration

Feed Rate 0.72 m/min

Stroke Frequency 381 1/min

Needle Penetration 11 mm

Tensile Strength (MD) 2.17 kN/m

Tensile Strength (XD) 3.7 kN/m

Fabric Area Density 351.40 g/m2

Fabric Thickness 3.51 mm

Permeability 0.06 m/s

Transmissivity (XD) 0.0000027 m3/m-s

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | Theta (De | Rel-Freq | Theta(rads | a1 | a2 | a3 |
| 2 | 0 | | | | | |
| 3 | 5 | 2.0 | | | | |
| 4 | 10 | 2.0 | | | | |
| 5 | 15 | 4.4 | | | | |
| 6 | 20 | 4.6 | | | | |
| 7 | 25 | 5.5 | | | | |
| 8 | 30 | 5.2 | | | | |
| 9 | 35 | 4.7 | | | | |
| 10 | 40 | 4.1 | | | | |
| 11 | 45 | 4.4 | | | | |
| 12 | 50 | 3.4 | | | | |
| 13 | 55 | 3.3 | | | | |
| 14 | 60 | 3. | | | | |
| 15 | 65 | 2.0 | | | | |
| 16 | 70 | 0. | | | | |
| 17 | 75 | 2.6 | | | | |
| 18 | 80 | 1.9 | | | | |
| 19 | 85 | 1.9 | | | | |
| 20 | 90 | 1.5 | | | | |

Influence of Process Parameters on Geotextile Properties

It was found that reorientation of the fibres from horizontal to a vertical direction as a result of depth of needle penetration and /or stroke frequency can highly influence geotextile properties.

**FIGURE 9.** Data entry form for prediction of geotextile properties.

with their respective coefficients of correlation. These coefficients of correlation are obtained from the comparison made between empirically modeled data and the corresponding measured values. These results show good correlation between the actual and calculated values.

### Development of Expert System for Needlepunched Geotextiles

The empirical models developed have formed the basis for an expert system with the primary aim of predicting the geotextile properties under a given set of process parameters. The expert system for laboratory equipment available to the authors has been developed in the form of a computer model using Delphi programming language [11]. The basic form for data entry is shown in Figure 9. Furthermore, the geometrical properties were also incorporated to compute the ODF. Therefore, the expert system can predict properties required for any desired application of geotextiles.

## CONCLUSIONS

A series of empirical relationships have been developed with the process parameters, namely, feed rate, stroke frequency, and depth of needle

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penetration to predict the properties of needlepunched geotextiles. Effects of these process parameters on geometrical and hydraulic properties of geotextiles are also investigated. It is found that reorientation of the fibers from horizontal to vertical direction as a result of depth of needle penetration and/or stroke frequency highly influences geotextile properties. Therefore, multifunctional needlepunched geotextiles can be produced by optimizing these parameters for desired geotextile properties. The geometrical properties such as fiber orientation and pore size distributions can also be controlled and modified specifically for any drainage and filtration based applications of geotextiles. The expert system developed from the above experimental results allowed a '*right first time*' approach to design geotextiles in a cost-effective manner.

The reported work is an ongoing research programme and the future work would include the prediction and comparison of geotextile properties based upon natural fibers.

## ACKNOWLEDGMENTS

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**Amit Rawal** has obtained his PhD in Advanced Materials from The University of Bolton. He received his Masters from The University of Manchester in the field of Technical Textiles. Recently, he has been awarded a Young Researcher Fellowship from the prestigious MIT, Cambridge for exemplary research in Computational Mechanics. Currently, he is working as a Post-Doctoral research fellow in CSIR, South Africa and focusing on developing novel geotextiles and its related products specifically for drainage and filtration media. His research interests include rheological properties of polymers, polymer flow modelling and structural mechanics of woven and nonwoven fibrous assemblies.

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